7-30-2018

An in situ probe-spacing-correcting thermo-TDR sensor to measure soil water content accurately

M. M. Wen
China Agricultural University

G. Liu
China Agricultural University

R. Horton
Iowa State University, rhorton@iastate.edu

K. Noborio
Meiji University

An in situ probe-spacing-correcting thermo-TDR sensor to measure soil water content accurately

Abstract

To reduce the possibility of probe deflections, conventional thermo-time domain reflectometry (T-TDR) sensors have relatively short probe lengths (≤4 cm). However, short probes lead to large errors in TDR-estimated soil water content (θv). In this study, two new 6-cm-long probe-spacing-correcting T-TDR (CT-TDR) sensors were investigated. Compared to conventional 4-cm-long T-TDR sensors, the 6-cm-long CT-TDR sensors reduced errors in TDR-estimated θv. Errors in heat pulse (HP) estimated θv because of probe deflections were reduced when linear or nonlinear probe spacing correcting algorithms were implemented. The 6-cm-long CT-TDR sensors provided more accurate θv estimations than do the conventional 4-cm-long TTDR sensors.

Keywords

probe deflection, probe length, probe spacing changes

Disciplines

Agricultural Science | Hydrology | Soil Science

Comments

This is the peer reviewed version of the following article: Wen, M. M., G. Liu, R. Horton, and K. Noborio. "An in situ probe-spacing-correcting thermo-TDR sensor to measure soil water content accurately." *European Journal of Soil Science* (2018), which has been published in final form at doi: 10.1111/ejss.12718. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions.

An *in situ* probe-spacing-correcting thermo-TDR sensor to measure soil water content accurately

M.M. WEN[a], G. LIU[a], R. HORTON[b] & K. NOBORIO[c]

[a]*Department of Soil and Water Sciences, College of Resources and Environment, China Agricultural University, Beijing 100193, China,* [b]*Department of Agronomy, Iowa State University, Ames, IA 50011, USA, and*

[c]*School of Agricultural, Meiji University, Kawasaki 2148571, Japan*

Correspondence: Gang Liu (liug@cau.edu.cn)

Running Title: Probe-spacing-correcting thermo-TDR sensor

Summary

To reduce the possibility of probe deflections, conventional thermo-time domain reflectometry (T-TDR) sensors have relatively short probe lengths (≤4 cm). However, short probes lead to large errors in TDR-estimated soil water content (θ_v). In this study, two new 6-cm-long probe-spacing-correcting T-TDR (CT-TDR) sensors were investigated. Compared to conventional 4-cm-long T-TDR sensors, the 6-cm-long CT-TDR sensors reduced errors in TDR-estimated θ_v. Errors in heat pulse (HP) estimated θ_v because of probe deflections were reduced when linear or nonlinear probe spacing correcting algorithms were implemented. The 6-cm-long CT-TDR sensors provided more accurate θ_v estimations than do the conventional 4-cm-long T-TDR sensors.

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1111/ejss.12718

Keywords: probe deflection, probe length, probe spacing changes.

Highlights:

- Short thermo-TDR sensor has shortcomings in determining soil water content.
- Changes in thermo-TDR probe spacing caused by deflections can be determined *in situ*.
- Correcting changed thermo-TDR probe spacing determines soil water content accurately.
- The 6-cm long thermo-TDR sensors determined soil water content more accurately than 4-cm long sensors.

Introduction

Soil water content and thermal properties are important for soil surface energy partitioning and for subsurface heat and water transfer. Time domain reflectometry (TDR) is widely used to determine soil water content (θ_v) (Robinson *et al*., 2008). The heat pulse (HP) method can determine thermal properties of soil (Bristow *et al*., 1994) and θ_v (Heitman *et al*., 2003). To determine θ_v and thermal properties simultaneously, Noborio *et al*. (1996) and Ren *et al*. (1999) developed the thermo-time domain reflectometry (T-TDR) sensor by combining HP and TDR sensors. The T-TDR sensor can also be used to determine soil bulk density (Ochsner *et al*., 2001).

There is a conflict between the optimal probe length for HP and TDR sensors. Dalton & van Genuchten (1986) recommend that TDR probes be at least 10-cm long, because probe length can affect the accuracy of waveform analysis, and shorter probes have relatively large uncertainties in estimating θ_v (Heimovaara, 1993). Commonly used HP probes have a diameter of ≤ 1.27 mm. Unaccounted for changes in probe spacing (r) can lead to errors in estimated specific heat (c) values (Wen *et al*., 2015). To minimize the possibility of changes in r because of deflections, the majority of HP probes are relatively short (≤ 4 cm). Therefore, most T-TDR probes are 4-cm-long or less. Short T-TDR probes, however, are not as accurate as long probes for determining θ_v.

Several methods are available to improve the performance of T-TDR sensors. Using an expensive cable tester or oscilloscope with a short rise time (≤ 200 ps) (Kelly *et al*., 1995) and performing data smoothing and filtering analysis on the waveforms (Wang *et al*., 2016) can improve TDR waveform analysis for short probes. To minimize probe deflection, Kamai *et al*. (2015) made robust probes by increasing their diameter. Compared with thin probes, however, thick probes can compact soil

(Rothe *et al*., 1997) and distort water flow around the probes (Hinnell *et al*., 2006).

In situ probe-spacing-correcting HP sensors can correct linear (Liu *et al*., 2013) and nonlinear probe deflections (Liu *et al*. 2016). If the correcting methods can be introduced effectively into T-TDR sensors with relatively long TDR probes, then, r can be determined accurately and errors in c and θ_v can be reduced. In addition, the accuracy of TDR-estimated θ_v with the longer T-TDR sensor will be improved.

In this study, we evaluated how accurately *in situ* probe-spacing-correcting T-TDR (CT-TDR) sensors (Figure 1a) with probe lengths of 6 cm could determine θ_v derived from TDR waveforms, and from HP we estimated soil specific heat.

Theory

The heat pulse (HP) method

The HP estimated θ_v is calculated as (Campbell *et al*., 1991):

$$\rho c = \rho_b c_s + \rho_w c_w \theta_v \,, \qquad (1)$$

where ρ_w (kg m^{-3}) and ρ_b (kg m^{-3}) are the water density and soil bulk density, respectively, and c_s (J kg^{-1} K^{-1}) and c_w (J kg^{-1} K^{-1}) are the specific heat of soil solids and water, respectively. The product ρc (J m^{-3} K^{-1}) is equal to the soil volumetric heat capacity (C).

Probe-spacing-correcting method. The linear model described by Liu *et al*. (2013) for the nonlinear model described by Liu *et al*. (2016) for linear and nonlinear probe deflection, respectively, are used for probe-spacing-correction.

The TDR method

An empirical relation between θ_v and K_a (dielectric constant of soil) (Topp *et al*., 1980) is used to calculate θ_v

$$\theta_v = -5.3\times10^{-2} + 2.92\times10^{-2} K_a - 5.5\times10^{-4} K_a^2 + 4.3\times10^{-6} K_a^3 \,. \quad (2)$$

Materials and methods

In this study, we carried out both HP and TDR measurements to test the application of the *in situ* CT-TDR sensor.

Heat pulse experiments

The 6-cm-long CT-TDR sensors used in this study had a probe diameter of 1.27 mm. Two kinds of 6-cm-long sensors were investigated: Sensor T6A (two thermistors (l) in each temperature probe, l_1=4 cm and l_2=2 cm) and Sensor T6B (three thermistors in each temperature probe, l_1=4.5 cm, l_2=3 cm and l_3=1.5 cm). Based on the results of Wen *et al*. (2015) and the strain relationship for a bar (Beer *et al*., 2006), Sensors T6A and T6B were used to test the linear and nonlinear models, respectively.

The HP experiments were performed on sand samples with known ρ_b over a wide range of θ_v (c_s=751 J kg^{-1} K^{-1} measured by differential scanning calorimetry (DSC) at 20°C). Additional details about probe deflection and HP measurements can be found in Wen *et al*. (2015).

The TDR experiments

Two types of TDR sensors were investigated: two 4-cm-long T-TDR sensors (T4A and T4B) and two 6-cm-long CT-TDR sensors (T6A and T6B). All the TDR sensors had a three-probe design. The TDR measurements were made at variable θ_v with known ρ_b in sandy clay soil and in sand, and waveforms were recorded by a TDR100 (Campbell Scientific, Inc. Logan, UT). The actual volumetric θ_v of each sample was determined by oven-drying to measure the gravimetric θ_v and multiplying the gravimetric value by the sample ρ_b. The actual θ_v values were used as the reference volumetric θ_v (θ_v_ref.).

Results and discussion

Heat pulse results

The HP-estimated θ_v values are presented in Figure 2; each value represents the average value derived from the two (for the linear model) or three (for the nonlinear model) thermistors in each temperature probe.

Figure 2 shows that, without corrections for r, deflections can cause large errors in the estimated θ_v values. The corrected θ_v values derived from the linear and nonlinear models are much closer to the actual θ_v_ref. values than are the uncorrected values.

For the linear model, we obtained a regression equation of

$$Y = 0.902\,X + 0.007 \qquad (R^2 = 0.826),$$

whereas for the nonlinear model, we obtained a regression equation of

$$Y = 0.981\,X + 0.005 \qquad (R^2 = 0.982).$$

These regression results indicate that the nonlinear model was more accurate than the linear model. However, the nonlinear model uses three thermistors, which requires several datalogger channels per sensor. In some situations, it may be advantageous to use the linear model which does not use as many channels.

Probe deflections caused larger errors in θ_v than in c (c data not shown), even after the r values were corrected. According to Heitman *et al*. (2003), errors in θ_v for the heat pulse method are due to a combination of parameters such as c_s, r, q (the energy input per unit length of heater per unit time of the HP sensor) and ΔT_m (the maximum temperature rise of the temperature curve). A change in r is just one of the sources of error in θ_v, so although r is corrected, errors in HP-estimated θ_v remain.

The TDR results

The TDR-estimated θ_v values (TDRθ_v) are shown in Figure 3. Results indicate that the accuracy of TDR-estimated θ_v increases with increasing probe length. The R^2 value for the 6-cm-long TDR probes (0.960) was larger than that for the 4-cm-long TDR probes (0.912). For a 5-cm-long TDR probe, Topp *et al*. (1984) reported an R^2 value of 0.957, which is between the values for our 4- and 6-cm-long probes. The difficulty in detecting the reflection points in a short probe TDR waveform (Heimovaara, 1993) might account for the relatively large errors and scattered data points for the 4-cm-long probes.

Although long TDR probes provided better estimates of θ_v than short ones, it does not mean that the longer is the probe length, the better is the performance of CT-TDR sensors. This is because long probes are more apt to deflect than short probes. In addition, the probe-spacing-correcting method relies on the assumption that soil is homogeneous. Therefore, in strongly heterogeneous soil, long probes might be more vulnerable to errors than short probes.

Conclusions

We introduced a new 6-cm-long CT-TDR sensor that combined the TDR and *in situ* probe-spacing-correcting HP methods. The HP results indicated that, after *in situ* probe-spacing corrections, sensors provided more accurate results than those that were uncorrected. The TDR results indicated that 6-cm-long TDR probes were more accurate than 4-cm-long TDR probes. The 6-cm-long CT-TDR sensor improved on shortcomings of the 4-cm-long T-TDR sensor.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (Grant No. 41771257 (G. Liu)), the National Key Research and Development Project of China (Grant No. 2016YFD0800102), China Scholarship Council award to Minmin Wen for one year of study at Iowa State University (201606350315), the US Army

Research Office Award W911NF1610287, the US National Science Foundation under Grant 1623806, and the USDA–NIFA Multi-State Project 3188. We thank Dr. Tusheng Ren for providing guidance on the thermo-TDR measurements.

Accepted Article

References

Beer, F.P., Johnston, E.R., DeWolf, J.T. & Mazurek, D., 2006. *Mechanics of Materials*, 4th edition. McGraw Hill, New York, NY.

Bristow, K.L., Kluitenberg, G.J. & Horton, R. 1994. Measurement of soil thermal properties with a dual-probe heat-pulse technique. *Science Society of America Journal*, **58**, 1288–1294.

Campbell, G.S., Calissendorff, C. & Williams, J.H. 1991. Probe for measuring soil specific heat using a heat-pulse method. *Soil Science Society of America Journal*, **55**, 291–293.

Dalton, F.N. & van Genuchten, M.Th. 1986.The time-domain reflectometry method for measuring soil water content and salinity. *Geoderma*, **38**, 237–250.

Heitman, J.L., Basinger, J.M., Kluitenberg, G.J., Ham, J.M., Frank, J.M. & Barnes, P.L. 2003. Field evaluation of the dual-probe heat-pulse method for measuring soil water content. *Vadose Zone Journal*, **2**, 552–560.

Heimovaara, T.J. 1993. Design of triple-wire time domain reflectometry probes in practice and theory. *Soil Science Society of America Journal*, **57**, 1410–1417.

Hinnell, A.C., Ferré, T.P.A. & Warrick, A.W. 2006. The influence of time domain reflectometry rod induced flow disruption on measured water content during steady state unit gradient flow. *Water Resources Research*, **42**, 466–480.

Kamai, T., Kluitenberg, G. & Hopmans, J.W. 2015. A dual-probe heat-pulse sensor with rigid probes for improved soil water content measurement. *Soil Science Society of America Journal*, **79**, 1059–1072.

Kelly, S.F., Selker, J.S. & Green, J.L. 1995. Using short soil moisture probes with high-bandwidth time domain reflectometry instruments. *Soil Science Society of America Journal*, **59**, 97–102.

Liu, G., Wen, M. Chang, X. Horton, R. & Ren, T. 2013.A self-calibrated DPHP sensor for in situ calibrating the probe spacing. *Soil Science Society of America Journal*, **77**, 417– 421.

Liu, G., Wen, M., Ren, R., Si, B., Horton, R. & Hu, K. 2016. A general in situ probe spacing correction method for dual probe heat pulse sensor. *Agricultural and Forest Meteorology*, **226–227**, 50–56.

Noborio, K., McInnes, K.J. & Heilman, J.L. 1996. Measurements of soil water content, specific heat, and thermal, conductivity with a single TDR probe. *Soil Science*, **161**, 22–28.

Ochsner, T.E., Horton, R. & Ren, T.S. 2001. Simultaneous water content, air-filled porosity, and bulk density measurements with thermo-time domain reflectometry. *Soil Science Society of America Journal*, **65**, 1618–1622.

Ren, T., Noborio, K. & Horton, R. 1999. Measuring soil water content, electrical conductivity, and thermal properties with a thermo-time domain reflectometry probe. *Soil Science Society of America Journal*, **63**, 450–457.

Robinson, D.A., Campbell, C.S., Hopmans, J.W., Hornbuckle, B.K., Jones, S.B., Knight, R., Ogden, F., Selker, J. & Wendroth, O. 2008. Soil moisture measurements for ecological and hydrological watershed scale observatories: a review. *Vadose Zone Journal*, **7**, 358–389.

Rothe, A., Weis, W., Kreutzer, K., Matthies, D., Hess, U. & Ansorge, B. 1997. Changes in soil structure caused by the installation of time domain reflectometry probes and their influence on the measurement of soil moisture. *Water Resources Research*, **33**, 1585–1593.

Topp, G.C., Davis, J.L. & Annan, A.P. 1980. Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. *Water Resources Research*, **16**, 574–582.

Topp, G.C., Davis, J.L., Bailey, W.G. & Zebchuk, W.D. 1984. The measurement of soil water content using a portable TDR hand probe. *Canadian Journal of Soil Science*, **64**, 313–321.

Wang, Z., Lu, Y., Kojima, Y., Lu, S., Zhang, M., Chen, Y. & Horton, R. 2016 Tangent line/second-order bounded mean oscillation waveform analysis for short TDR probe. *Vadose Zone Journal*, **15**. doi:10.2136/vzj2015.04.0054

Wen, M., Liu, G., Li, B., Si, B. & Horton, R. 2015. Evaluation of a self-correcting dual probe heat pulse sensor, *Agricultural and Forest Meteorology*, **200**, 203–208.

FIGURE CAPTIONS

Figure 1 (a) Side view of the cross section of the probe-spacing-correcting thermo-TDR (CT-TDR) sensor and (b) diagram for a deflected CT-TDR sensor (nonlinear outward deflection). Ⅰ, Heating probe; Ⅱ and Ⅲ, temperature probes; 4, heating wire; 5–10, thermistors (5, thermistor 1; 6, thermistor 2; 7, thermistor 3; 8, thermistor 4; 9, thermistor 5; 10, thermistor 6); 11, epoxy plug; 12, coaxial cable; ϕ, deflected angle; l_i, the distance of thermistor i to the surface of epoxy plug; r_{i0}, initial probe spacing for thermistor i; r_i, the changed probe spacing for thermistor i; Δr_i, The displacement of thermistor i.

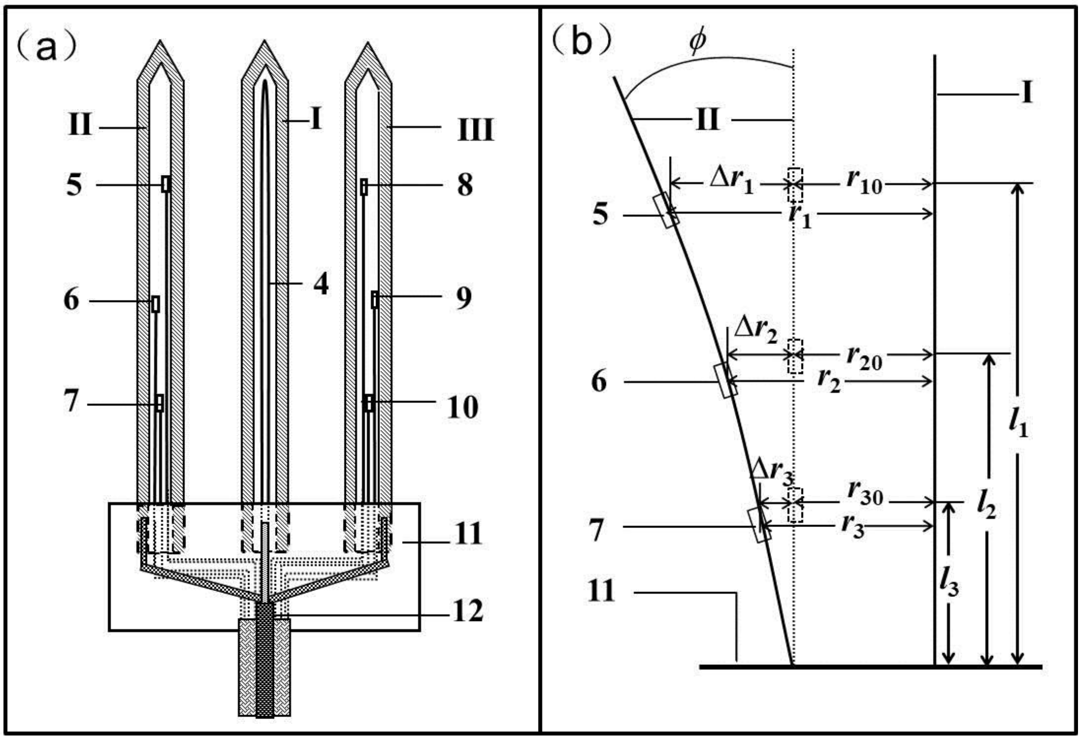

Figure 2 (a) Heat-pulse estimated water content values (HPθ_v) plotted against actual values of reference volumetric water content (θ_v_ref.) for sand corrected with linear model and (b) heat-pulse estimated water content values (HPθ_v) plotted against actual values of reference volumetric water content (θ_v_ref.) for sand corrected with nonlinear model. The black solid line is the 1:1 line.

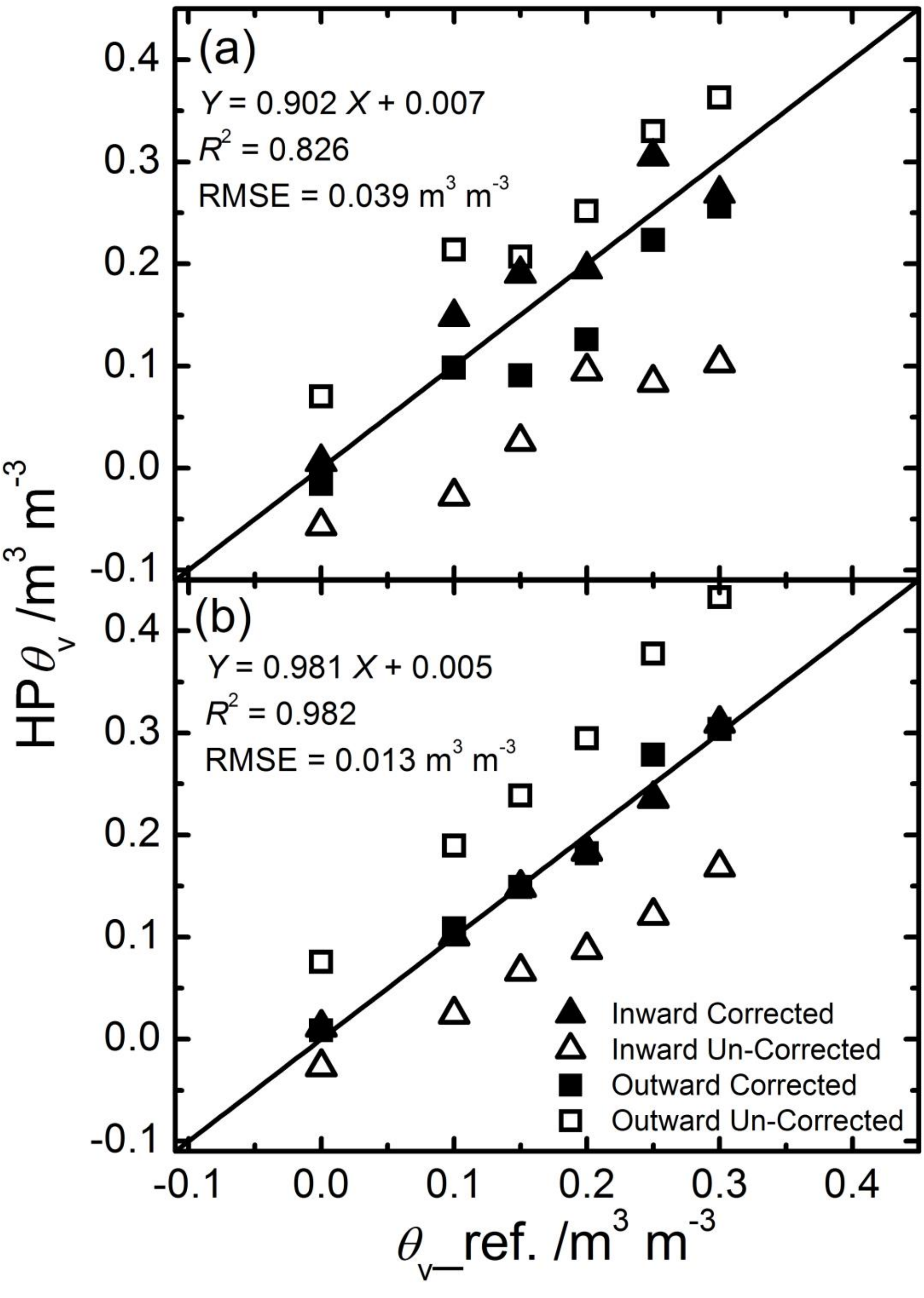
(a)
Y = 0.902 X + 0.007
R^2 = 0.826
RMSE = 0.039 m³ m⁻³
(b)
Y = 0.981 X + 0.005
R^2 = 0.982
RMSE = 0.013 m³ m⁻³
Inward Corrected
Inward Un-Corrected
Outward Corrected
Outward Un-Corrected
HPθ_v /m³ m⁻³
θ_v_ref. /m³ m⁻³
0.4
0.3
0.2
0.1
0.0
-0.1

Figure 3 (a) The TDR estimated water content (TDRθ_v) for sand and sandy clay by T4 probes and (b) the TDR estimated water content (TDRθ_v) for sand and sandy clay by T6 probes plotted against reference volumetric water content values (θ_v_ref.). The black solid line is the 1:1 line and the dashed lines enclose a 95% prediction interval.